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Anh-Minh Tang
École nationale des ponts et chaussées

Jean-Michel Pereira
École nationale des ponts et chaussées

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A simple method for numerical modelling of mechanical behaviour of an energy pile

N. YAVARI*, A. M. TANG*, J.-M. PEREIRA* and G. HASSEN*

A commercial numerical code was used to simulate the mechanical behaviour of energy piles under thermo-mechanical loadings. The thermal load was simply simulated by imposing on the pile volumetric strains calculated from the coefficient of thermal expansion of the material. Simulations were performed for two existing in situ experiments and one experiment performed using a physical laboratory model. Comparison between the simulations and experimental results shows that this decoupling method can satisfactorily predict the experimentally observed phenomena of pile head movement under thermal cycles at various mechanical loads and change of pile axial load along the pile under thermal cycles. The results highlight the important role played by thermal volume change of the pile on the mechanical behaviour of the energy pile under thermo-mechanical loadings.

KEYWORDS: piles; soil/structure interaction; temperature effects

NOTATION

c	soil cohesion
E	elastic modulus
α	volumetric coefficient of thermal expansion
γ	density
ν	Poisson's ratio
ϕ	internal friction angle
Ψ	dilation angle

INTRODUCTION

Energy piles are double-function foundations as they exchange heat with the surrounding soil while transferring structural load to the ground. Although having been used in the world of construction for more than three decades, various aspects of the technology are relatively unknown. Existing studies show that heating can

- produce additional stresses in the pile
- reduce adhesion forces at the pile interface
- disturb the thermal equilibrium of soil due to non-balanced heat extraction–injection during heating and cooling cycles (Fromentin *et al.*, 1999).

From an engineering point of view, it would thus be useful to have a numerical code to predict pile behaviour under thermo-mechanical loads and, accordingly, consider appropriate parameters and safety factors in design procedures. Some attempts have been made to produce such a program, from complicated finite-element codes to simpler tools, particularly based on the load transfer method (Laloui *et al.*, 2006; Knellwolf *et al.*, 2011; Peron *et al.*, 2011; Suryatriyastuti *et al.*, 2012).

In the present work, a commercial finite-element code that is well suited to geotechnical analyses was used to model the mechanical behaviour of energy piles under thermo-mechanical loadings. Thermal loading was simply simulated by imposing on the pile volumetric strains corresponding to thermal strains. The simulations were compared with existing data on in situ and physical model tests.

EXPERIMENTAL STUDY

Three existing experimental studies were considered. The first one corresponds to the in situ tests reported by Laloui *et al.* (2003). A pile situated below a building under construction was equipped with a heating system, load cells, strain gauges and thermometers. The drilled pile diameter was 0·88 m and its length was 25·8 m. The geological profile is summarised in Table 1. At various stages of the construction of the building, the temperature of the pile was increased by approximately 15°C and then the system was left to cool to the initial temperature. The first test (T1) was performed before the start of construction when the pile head was free to move. The other tests (T2–T7) correspond to the heating/recovery test at the end of each construction stage. The results obtained show pile head displacement and variation of axial strain along the pile under different head loads during heating/recovery tests.

The second study considered is that presented by Bourne-Webb *et al.* (2009) and Amatya *et al.* (2012). A loading-test pile, 0·55 m in diameter and 23 m in length, including pipe loops for temperature control was installed in London clay. After applying a constant mechanical load at the pile head, heating/cooling cycles were applied to the pile; the temperature of the fluid circulating in the pile was varied between −2·5°C and 36°C. Temperature and strain were measured at various locations along the pile during the thermo-mechanical loading. Movement at the pile head was also recorded.

In the third work, Kalantidou *et al.* (2012) studied soil/pile interaction while changing the temperature of the pile. A model pile – a closed-end aluminium tube of 20 mm external diameter and 600 mm length having its surface coated with sand – was embedded in compacted dry sand. After applying axial load to the pile head, the pile was

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*Université Paris-Est, Laboratoire Navier (UMR 8205), CNRS, ENPC, IFSTTAR, F-77455, Marne-la-Vallée, France

Table 1. Constitutive parameters of soils

Study[a]	Material	Depth: m	Drainage condition	γ: kN/m^3	c: kPa	ϕ: degrees	Ψ: degrees	E: MPa	ν
1	Alluvial soil	0–5·5	Drained	20·0	5	30	0	260	0·30
	Alluvial soil	5·5–12·0	Drained	19·5	3	27	0	260	0·30
	Sandy gravelly moraine	12·0–21·7	Drained	20·0	6	23	0	450	0·35
	Bottom moraine	21·7–25·1	Drained	22·0	20	27	0	630	0·35
	Molasse	25·1–31·0	Undrained	25·5	4	25	0	3000	0·22
2	Made ground (sand and gravel)	0–4	Drained	19·0	0	35	0	13	0·30
	London clay	>4	Undrained	20·0	20	25	0	70	0·30
3	Fontainebleau sand	0–0·85	Drained	15·1	0	36·5	0	340	0·30

[a]1, Laloui *et al.* (2003); 2, Bourne-Webb *et al.* (2009); 3, Kalantidou *et al.* (2012)

heated from 25°C to 50°C and the system was then left to cool to 25°C. The pile temperature and pile head displacement were monitored.

NUMERICAL MODELLING

Methods

The two-dimensional finite-element program Plaxis 2D was used to model the behaviour of energy piles from the three studies mentioned above. The models were considered to be axisymmetric and the dimensions were exactly the same as those of the experiments. In the case of in situ tests, extension of the simulated domain was chosen to be large enough to avoid boundary effects (at least 30 times the pile diameter). In the case of the physical model (Kalantidou *et al.*, 2012), the dimensions of the soil container were precisely known and the same sizes were chosen in the simulation. As an example, the mesh used for simulating the test presented by Laloui *et al.* (2003) is shown in Fig. 1.

The pile was modelled as an isotropic linear elastic non-porous material. For the soil, an isotropic linear elastic material with a failure criterion of Mohr–Coulomb type was chosen. The constitutive drained parameters and the drainage conditions are summarised in Tables 1 and 2. The parameters and the drainage conditions for the case of Laloui *et al.* (2003) were chosen according to the numerical studies reported by Laloui *et al.* (2006). For the Bourne-Webb *et al.* (2009) study, parameters and drainage conditions were chosen following Amatya *et al.* (2012), Reeves *et al.* (2006) and Karakus & Fowell (2005). For the study of Kalantidou *et al.* (2012), the soil parameters were chosen according to those proposed by De Gennaro *et al.* (2008) for Fontainebleau sand. To evaluate the pile stiffness, considering that the pile used was an empty aluminium cylinder, the modulus of elasticity was calculated for the equivalent section.

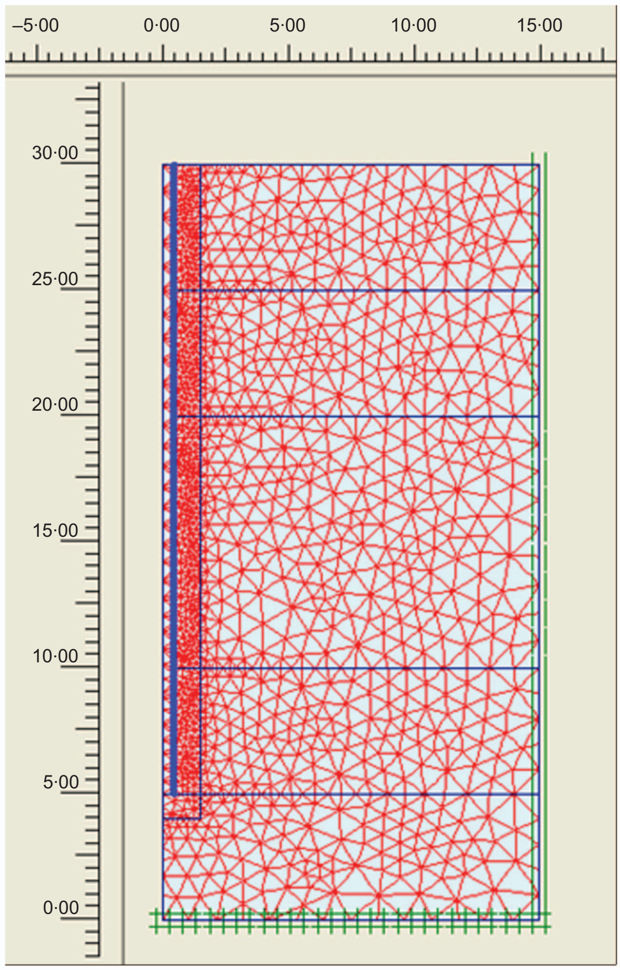

Fig. 1. Utilised mesh in the work of Laloui *et al.* (2003)

Table 2. Constitutive pile parameters

Study	Pile diameter: m	E: GPa	ν	α: 10^{-6}/°C
Laloui *et al.* (2003)	1·000	29·2	0·20	30·0
Bourne-Webb *et al.* (2009)	0·550	40·0	0·20	25·5
Kalantidou *et al.* (2012)	0·020	13·0	0·33	66·0

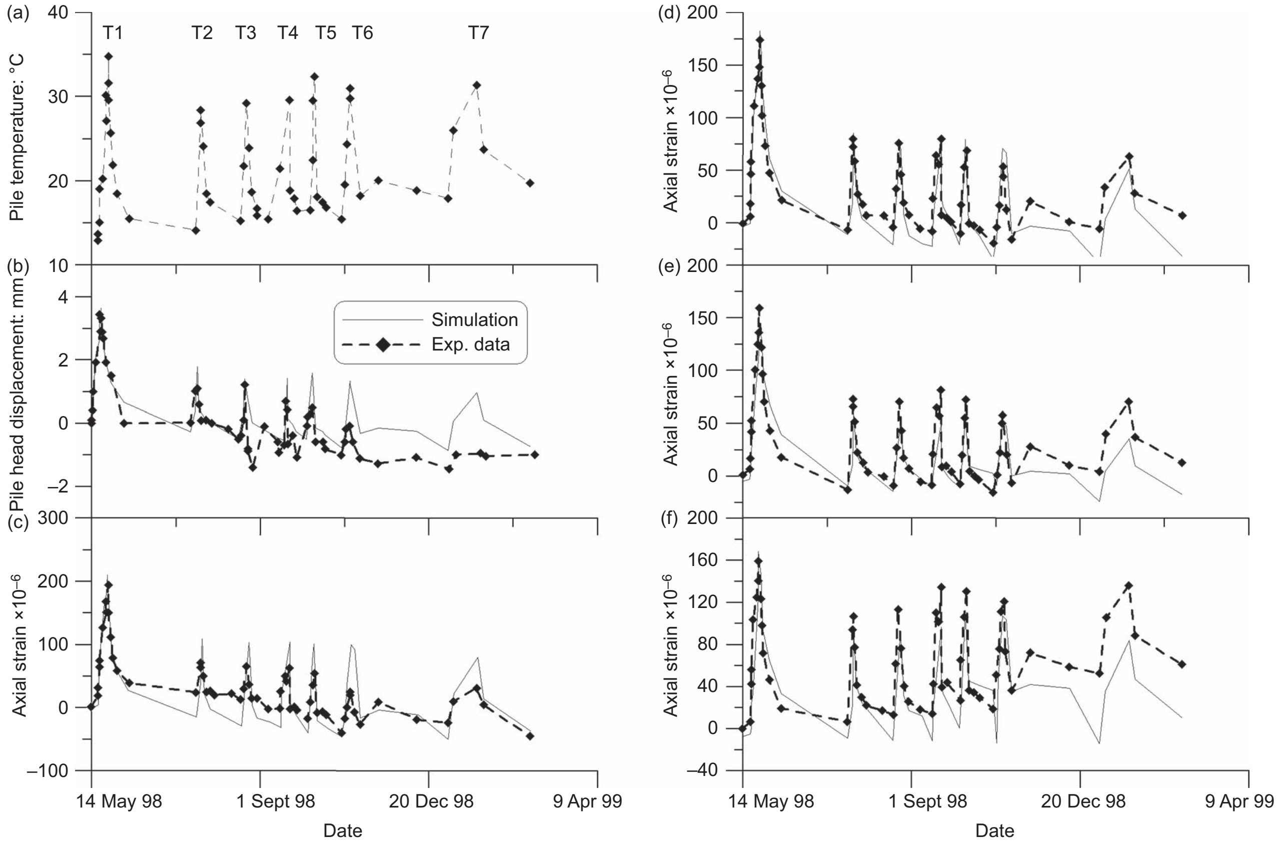

Fig. 2. Tests reported by Laloui *et al.* (2003): (a) pile temperature; (b) pile head displacement; (c) pile axial strain at 2·5 m depth; (d) pile axial strain at 10·5 m depth; (e) pile axial strain at 16·5 m depth; (f) pile axial strain at 24·5 m depth

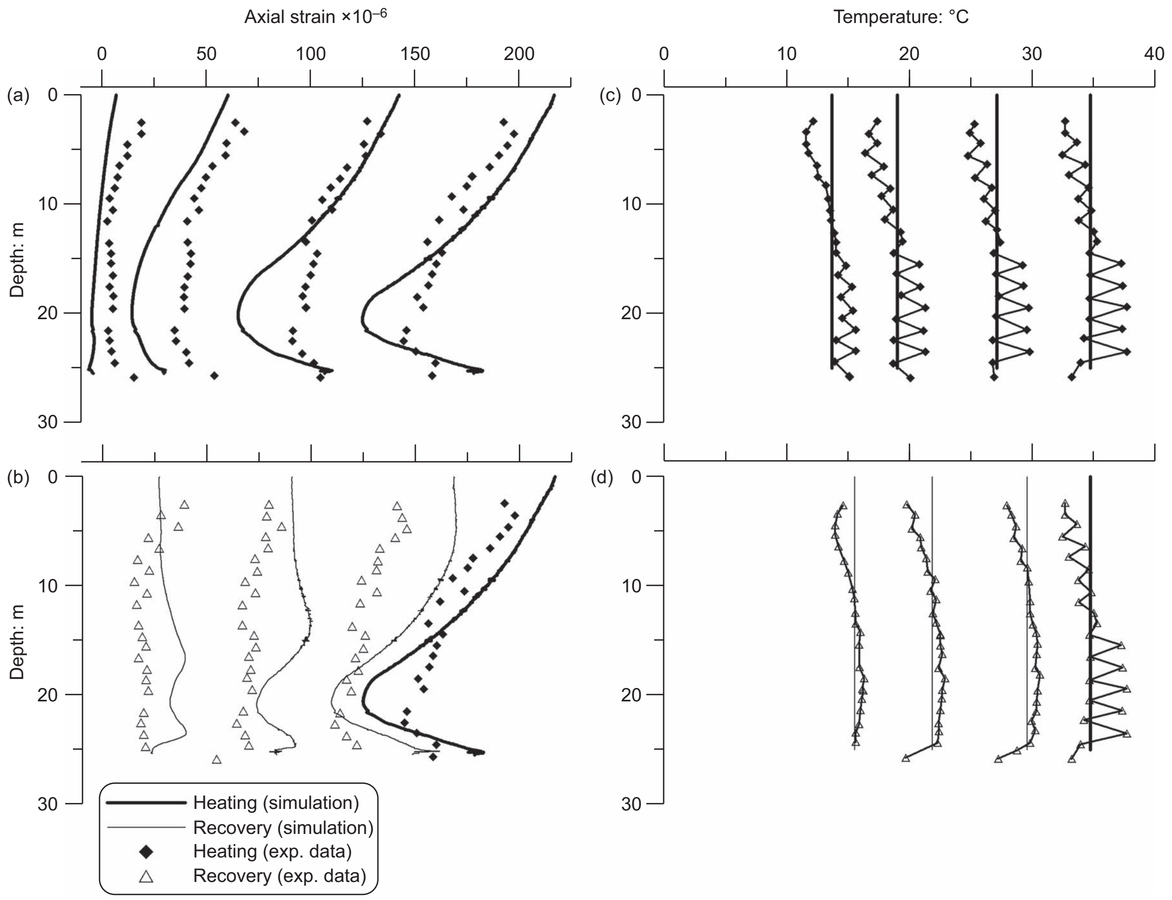

Fig. 3. Test T1 of Laloui *et al.* (2003): (a) pile axial strain distribution during heating; (b) pile axial strain distribution during recovery; (c) temperature evolution of pile during heating; (d) temperature evolution of pile during recovery

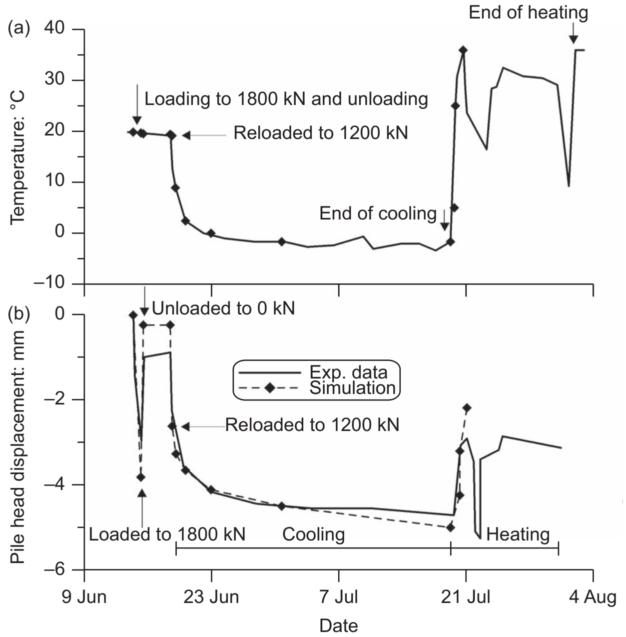

Fig. 4. (a) Temperature applied to the pile and (b) pile head displacement for the test presented by Bourne-Webb *et al.* (2009)

For the three cases, the soil/pile interface was considered perfectly rough; in other words, no interface element was added. This assumption does not seem unrealistic considering the concrete surface of the in situ piles and the sand-coated surface of the small-scale model pile. Note that interface elements are usually used when studying soil/pile interaction under complex mechanical loading, including cyclic and lateral ones (Nogami *et al.*, 1992; Said, 2004; Yang & Jeremić, 2005). In the present study, the mesh was refined in this zone, where significant stress gradients were expected.

To simulate thermal effects on mechanical behaviour, volumetric thermal deformation $\alpha\Delta T$ corresponding to temperature change ΔT was imposed on the pile (α is the volumetric coefficient of thermal expansion). For simplicity, temperature variation along the pile was neglected in the simulations and a mean value was considered in each step. Thermal expansion of the soil was not considered. This decoupling between thermal and mechanical effects permits the use of existing numerical codes and simple computations.

To model the boundary conditions at the pile head in the experiments of Bourne-Webb *et al.* (2009) and Kalantidou *et al.* (2012), only axial force (equal to that imposed in the experiments) was applied. In the case of Laloui *et al.* (2003), as the pile head was restrained by the building, axial force equal to that measured at the pile head during each step was imposed.

Results

The results obtained from the test presented by Laloui *et al.* (2003) and the simulation results are shown in Figs 2 and 3. Seven heating/recovery cycles were applied, with each cycle corresponding to a stage of the construction of the building. Figure 2(a) shows the change of mean temperature along the pile for each heating/recovery cycle. The pile head displacement during these cycles is presented in Fig. 2(b). Pile axial strains measured at various depths are shown in Figs 2(c)–(f). Comparison between the simulation and the experimental results shows that the mechanical behaviour of the pile can be predicted correctly, not only in terms of pile head displacement but also in terms of axial strain at various depths.

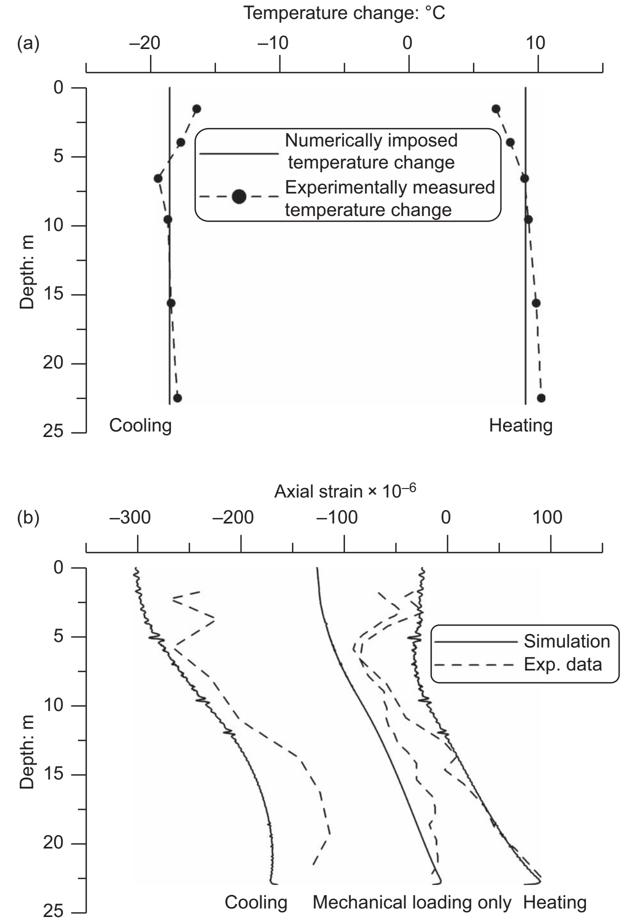

Fig. 5. Test presented by Bourne-Webb *et al.* (2009): (a) profile of temperature along the pile; (b) pile axial strain distribution

For further comparison, Figs 3(a) and 3(b) show the axial strain profiles (measured and modelled) along the pile at the end of each heating (or recovery step) for the first test (T1) before construction had started. Figures 3(c) and 3(d) show temperatures measured and modelled along the pile. Strain profiles show generally good agreement between the simulation and the measured results, although in the actual test the behaviour seems rather reversible in the recovery phase. Discrepancies between the simulation and experimental data can be explained partly by the difference in the temperature profiles. Localised deflections observed in both test and modelling results (Figs 3(a) and 3(b)) can be explained by the variability in soil properties with depth (Table 1).

The results obtained from the tests presented by Bourne-Webb *et al.* (2009) are shown in Figs 4 and 5. During the test, the pile was first loaded to 1800 kN and then unloaded. Reloading was performed up to 1200 kN. From the initial temperature (20°C), the pile was cooled using circulating fluid at a temperature of about −2·5°C kept constant for about 1 month. The fluid was then heated to about 36°C (Fig. 4(a)). Figure 5(a) shows the temperature changes measured along the pile (as detailed in Bourne-Webb *et al.*, 2009) for the end of the cooling phase and the end of the subsequent heating phase. It can be seen that the cooling phase decreased the average pile temperature by 18°C and the pile temperature is 9°C higher than

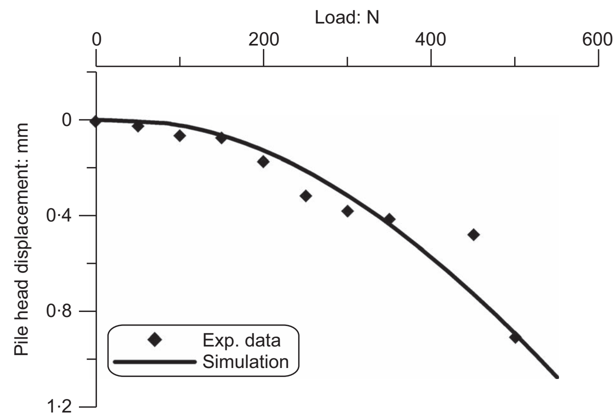

Fig. 6. Load–settlement curve of Kalantidou *et al.* (2012)

the initial one at the end of the heating phase. Figure 4(b) shows pile head displacement during different stages. Good agreement between numerical and experimental results was observed during mechanical and cooling steps, but the simulations overestimated pile head heave during heating. Figure 5(b) shows the axial strain profiles along the pile for three stages – the end of mechanical loading, end of cooling and end of heating. The results recorded by strain gauges (after Amatya *et al.* (2012)) during different phases are in good agreement with the simulation.

The load–settlement curve obtained from the work of Kalantidou *et al.* (2012) is shown in Fig. 6. The results obtained during the heating/recovery tests under constant load are shown in Fig. 7. Without pile head load (Fig. 7(a)), the simulation is similar to the experimental results. This confirms that the pile head displacement corresponds to the thermal expansion of the pile, as suggested by Kalantidou *et al.* (2012). Under a pile head load of 200 N (Fig. 7(b)), a large disparity between the two sets of curves can be seen. During the first heating, pile heave is about double that in the test. Furthermore, compared with the numerical results, the pile behaviour seems more reversible. On the contrary, at pile head loads of 400 N and 500 N (Fig. 7(c)), good agreement was found. It should be stressed that in 1 ***g*** physical models, stress levels are relatively low; this increases experimental inaccuracies and modelling difficulties and could explain some of the discrepancies observed.

DISCUSSION

Mechanical behaviour of an energy pile is affected by the thermal volume change of pile and soil, soil and pile parameter changes due to temperature changes, and sensitivity of soil/pile interface characteristics to thermal loading (Laloui *et al.*, 2006). In the present work, for the sake of simplicity, only the thermal volume change of the pile is taken into account. This decoupling procedure was also used by Peron *et al.* (2011). The present study shows generally good agreement between experimental data and numerical simulation. This means that the mechanical behaviour of the pile is mainly governed by its thermal volume change, and the thermal volume change of the soil has less influence. The disparity between the experimental results and the simulations could be explained by the assumption that the temperature of the pile is homogenous. The second reason could be related to the lack of interface element in the numerical simulation and the third to the assumption of no thermal strain in the soil.

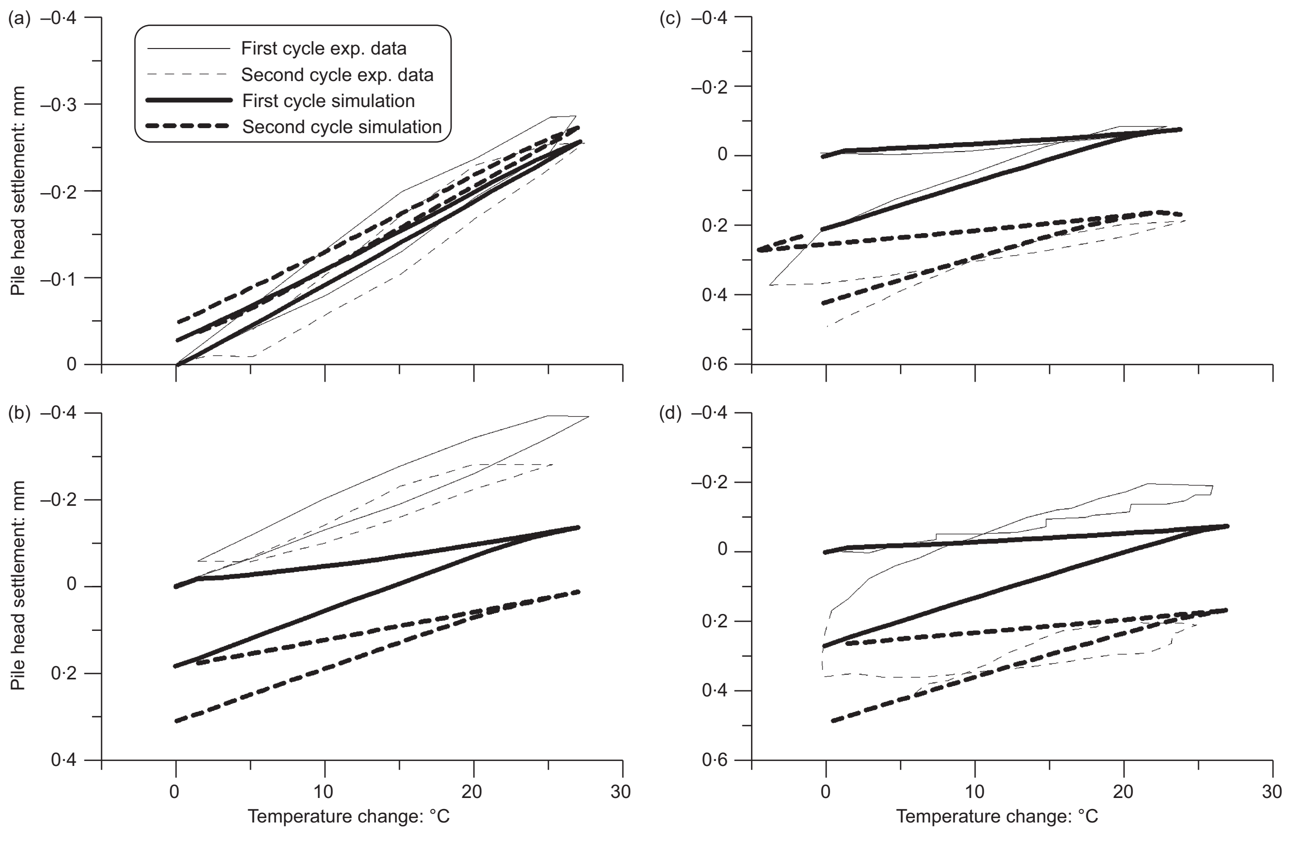

Fig. 7. Temperature–settlement curves under different head loads reported by Kalantidou *et al.* (2012): (a) 0 N, (b) 200 N, (c) 400 N, (d) 500 N

It is important to distinguish between 'cooling' and 'recovery' notions. In the experiments of Laloui *et al.* (2003) and the mentioned small-scale test, the pile temperature decreases with time, not by directly imposing low temperatures. In other words, the rate of temperature change is smaller in the recovery period, which is comparable to drained mechanical loadings in general. Time effects related to loading phases are not accounted for in the current approach. This might be one source of the overestimation of irreversible deformations by the model in the recovery phase of Laloui *et al.* (2003). Another factor could be that the application of thermal volume changes to the pile while no thermal volume changes are considered for the surrounding soil might induce a more abrupt response of the pile. In practice, in the presence of heat diffusion from a pile to soil, the temperature field (and the consequent expansions or contractions) would be more uniform, which could lead to a more uniform axial deformation distribution, as observed in the experiments presented by Laloui *et al.* (2003).

CONCLUSION

A commercial finite-element code for geotechnical design was used to simulate a pile under thermo-mechanical loading. An equivalent thermal volumetric deformation was applied to the pile. This simplified method was examined by simulating two in situ tests on energy piles and one laboratory physical model test. The numerical results were compared with experimental measurements, and good agreement was found.

At the observed scale, the proposed method seems to give satisfactory results in simulating mechanical behaviour under coupled thermo-mechanical loadings. It could thus be used as a simple method in design procedures when fully coupled analysis methods are not envisioned.

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